October 1996

Meteorites from Mars!

Earth Science and Solar System Exploration Division
NASA Lyndon B. Johnson Space Center
Houston, Texas

Twelve unusual meteorites are almost certainly pieces of Mars that were blasted off the red planet by meteoroid impact. They have been called SNC meteorites after the three type samples, **S**hergotty, **N**akhla, and **C**hassigny, or now simply martian meteorites. All twelve meteorites are igneous rocks crystallized from lava in the crust of a parent body. They are, however, distinct from typical igneous meteorites from asteroids in ways that suggest that the SNC meteorites come from a much larger body, a planet. All but one of these meteorites are very young (1.3 Ga or less) compared to ancient ages for other igneous meteorites (about 4.5 Ga). They also have higher oxygen fugacities and contents of water and other volatiles, contain minerals with ferric iron, and form a distinct trend in oxygen isotopic composition. The conclusive evidence that SNC meteorites are from Mars is the analysis of gases trapped in glass inclusions in EETA79001, which chemically and isotopically match gases measured in the unique martian atmosphere by the Viking lander spacecraft (Figure 1).

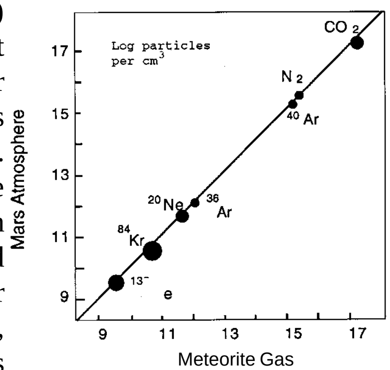


Figure 1. *Comparison of Viking-measured Mars atmosphere to trapped gases in Shergottite meteorite EETA79001.*

The martian meteorites represent five different types of igneous rocks, ranging from simple plagioclase-pyroxene basalts to almost monomineralic cumulates of pyroxene or olivine. The meteorites and their rock types are listed in Table 1. Photographs of whole rocks and thin sections of a basalt and a cumulate are illustrated below. All of the meteorites solidified near the martian surface by crystallization from a cooling magma. Some of the shergottite basalts have close to magma compositions, while the other martian meteorites are dominated by accumulation of olivine and/or pyroxene. None of the martian meteorites are surface samples in that they have not been exposed to extensive weathering or irradiation by cosmic rays. The martian soil analyzed by Viking appears to be a weathered basalt which could have been of shergottite composition.

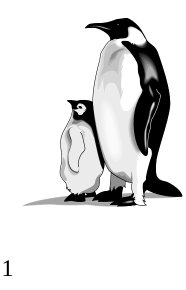
The only natural process capable of launching martian rocks to Earth is meteoroid impact. To be ejected from Mars a rock must reach the escape velocity of 5 km/sec, which is more than five times the muzzle velocity of a hunting rifle. During impact the kinetic energy of the incoming projectile causes shock deformation, heating, melting, and vaporization, as well as crater excavation and ejection of target material. The martian meteorites show low to moderate degrees of shock that appear to require a special mechanism to boost them to the escape velocity and eject them from Mars. The impact and shock provide an explanation for why the martian meteorites are all igneous rocks. Martian sedimentary rocks, and certainly soil, may not be sufficiently consolidated to survive the impact as intact rocks which might later land on Earth as meteorites.

Table 1. Martian Meteorites

Name	Classification	Mass (kg)	find/fall	year
Shergotty	S - basalt (pyx-plag)	4.00	fall	1865
Zagami	S - basalt	18.00	fall	1962
EETA79001	S - basalt	7.90	find-A	1980
QUE94201	S - basalt	0.012	find-A	1995
ALHA77005	S - lherzolite (ol-pyx)	0.48	find-A	1978
LEW88516	S - lherzolite	0.013	find-A	1991
Y793605	S - lherzolite	0.018	find-A	1995
Nakhla	N - clinopyroxenite	40.00	fall	1911
Lafayette	N - clinopyroxenite	0.80	find	1931
Gov. Valadares	N - clinopyroxenite	0.16	find	1958
Chassigny	C - dunite (olivine)	4.00	fall	1815
ALH84001	- orthopyroxenite	1.90	find-A	1993

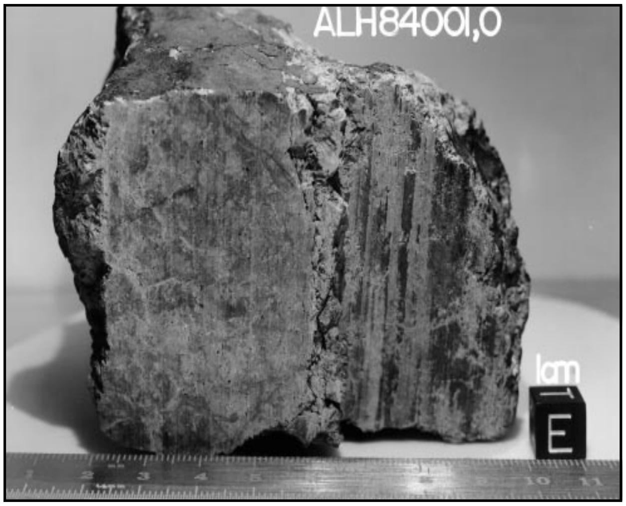
Classification: S = shergottite, N = nakhlite, C = chassignite, ALH84001 is none of these.

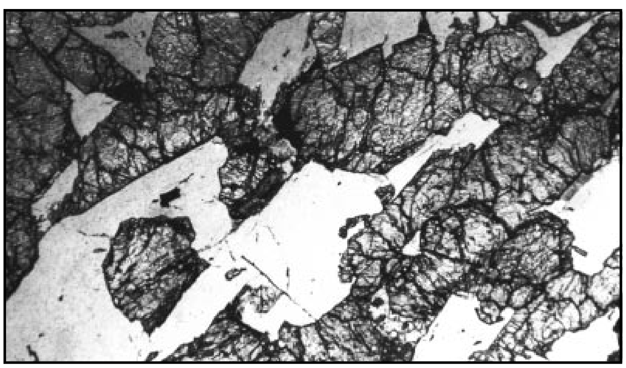
find-A designates Antarctic meteorites (all recent finds). *Year* is recovery date for non-Antarctic meteorites and date of martian classification for Antarctic meteorites.

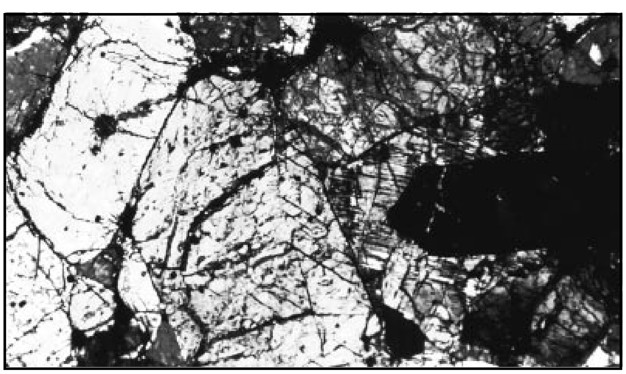


For more information write to:
Antarctic Meteorites, Mail Code SN2
NASA Johnson Space Center
Houston, Texas 77058

http://www-curator.jsc.nasa.gov/curator/antmet/antmet.htm







Thin section of martian meteorites (A. Treiman, LPI). Basaltic shergottite shows melt texture of pyroxene and plagioclase mineral (top). Dunite Chassigny shows the cumulate texture of olivine in polarized light (bottom).

Antarctic martian meteorites *(R. Score, JSC). ALHA77005 lherzolitic shergottite (top left) has a splotchy dark-light structure. EETA79001 basaltic shergottite (above) has light-colored xenoliths and dark glasses containing trapped martian atmosphere. ALH84001 orthopyroxenite (left) has a splotchy texture and tiny scattered carbonates.*

Volcanism and Impact

What was the timing of events?

Studies of the chronology of martian meteorites can distinguish various events in the history of the meteorites and give ground truth to martian geology. Different isotopes date distinct events. Long-lived radiogenic isotopes date planetary differentiation and igneous formation ages; $^{40}Ar/^{39}Ar$ can sometimes distinguish a separate ancient impact age. Cosmogenic isotopes date both the exposure age of the rocks in space as small (meter-sized) objects, which may also define the ejection time from Mars, as well as the terrestrial ages, which begin with the arrival of the rocks on Earth.

Radiogenic isotope studies of the shergottites yield a whole-rock model age of about 4.5 Ga. This suggests that planetary differentiation on Mars took place immediately after accretion and that the core, mantle and crust were isolated thereafter. The single ancient martian meteorite, ALH84001, has a formation age of about 4.5 Ga, an apparent shock age of 4.0 Ga, and an exposure age of 16 Ma. It represents the product of igneous melting and crystallization in the earliest martian crust. It is surprising that chance should cause us to find as meteorites only a piece of the martian crust that is as old as the oldest Apollo lunar samples, and pieces as young as the youngest martian surfaces, but no samples of intermediate age.

The nakhlites and Chassigny have formation ages of 1.3 Ga, much younger than ALH84001, and exposure ages of about 12 Ma (Figure 2). These two distinct rock types appear to be tied to the same geologic province. Similarly most of the basaltic and lherzolitic shergottites share a formation age of about 170 Ma and an exposure age of about 3 Ma. Basaltic shergottite EETA79001 has the same formation age, but a lower exposure age (0.7 Ma). Attempts to model a relationship between the shergottites and nakhlites-Chassigny based on mineralogy, and major and trace element compositions have shown that they are not simply related to the same magma or mantle source. Thus we conclude that partial melting in the mantle produced mafic magmas like those parental to the martian meteorites at intervals throughout Mars' history.

Clustering of martian meteorites into three groups based only on rock type, formation age and exposure age (Figure 2) suggests that these three groups represent sampling of three distinct martian sites by at least three distinct impacts in the last 15 Ma. The site for ALH84001 is presumably somewhere in the ancient cratered highlands of Mars' southern hemisphere and the two sites for samples having young formation ages (<1.3 Ga) probably are in the northern volcanic plains of Mars. However, integrating interpretations based on sample chemistry with those based on impact crater modeling and orbital mechanics is not straightforward. Two leading mechanisms for ejecting material off Mars, without melting or severely shocking the meteoroids, involve spallation from a free surface and gas drag resulting from vapor clouds generated by the impact. These mechanisms allow ejection of small, meteorite-sized fragments off Mars from relatively small craters.

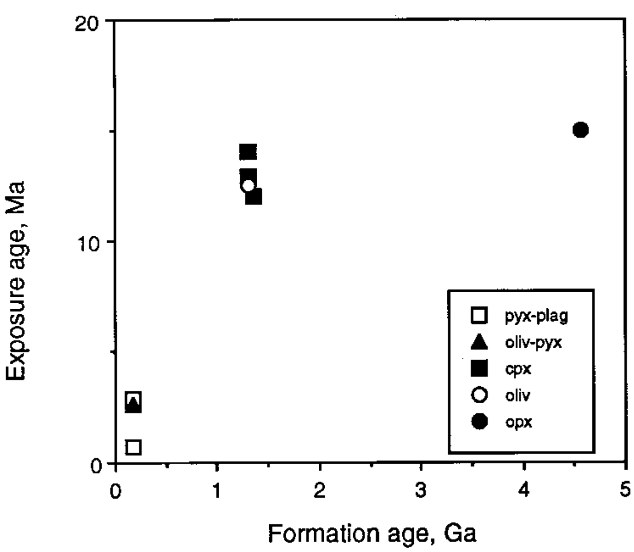
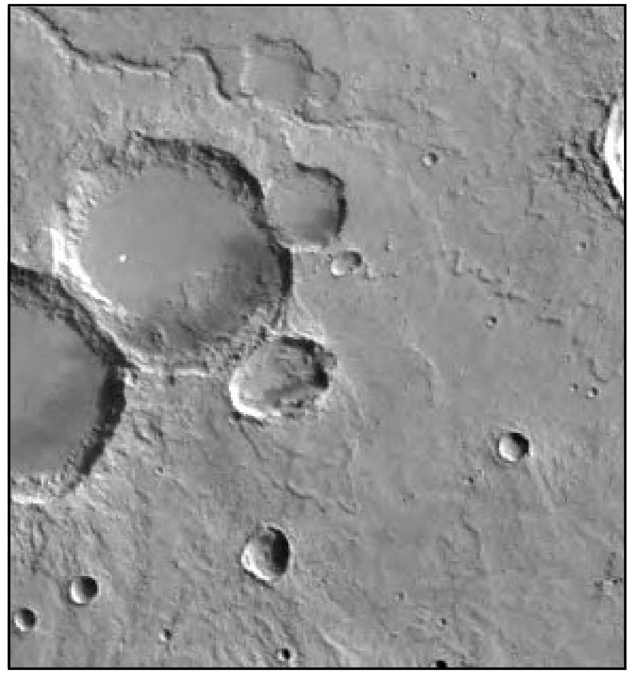
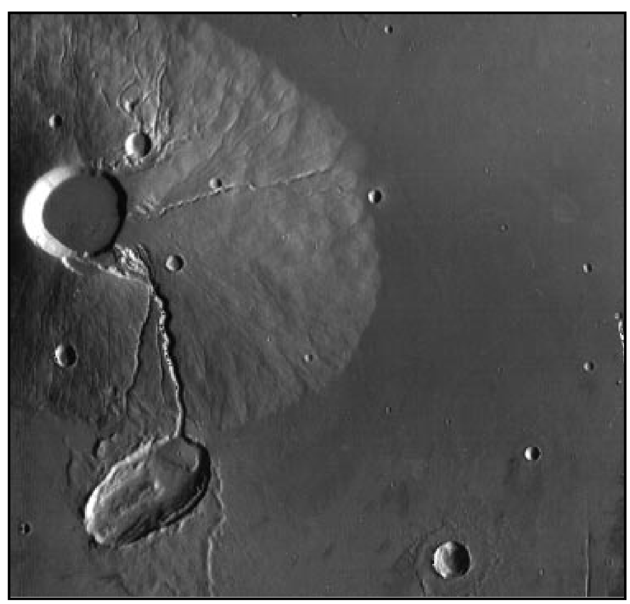


Figure 2. *Formation and exposure ages of martian meteorites.*

Recent modeling suggests that small rocky fragments ejected from Mars can be delivered to Earth in time periods encompassed by the meteorite exposure ages. If these models are accurate, then the numerous small craters on martian surface suggest that many fragments have been placed in solar orbit, and the question becomes "why is the range of crystallization ages and cosmic ray exposure ages so restricted?"



Possible source crater for ALH84001. *A candidate source crater for the oldest martian meteorite is this 23 x 15 km oval crater in the ancient terrain near areas that show evidence of ground water.*



Possible source crater, SNC. *A candidate source crater for young martian meteorites is this oval crater which sits on the flanks of a young volcano.*

Water on Mars

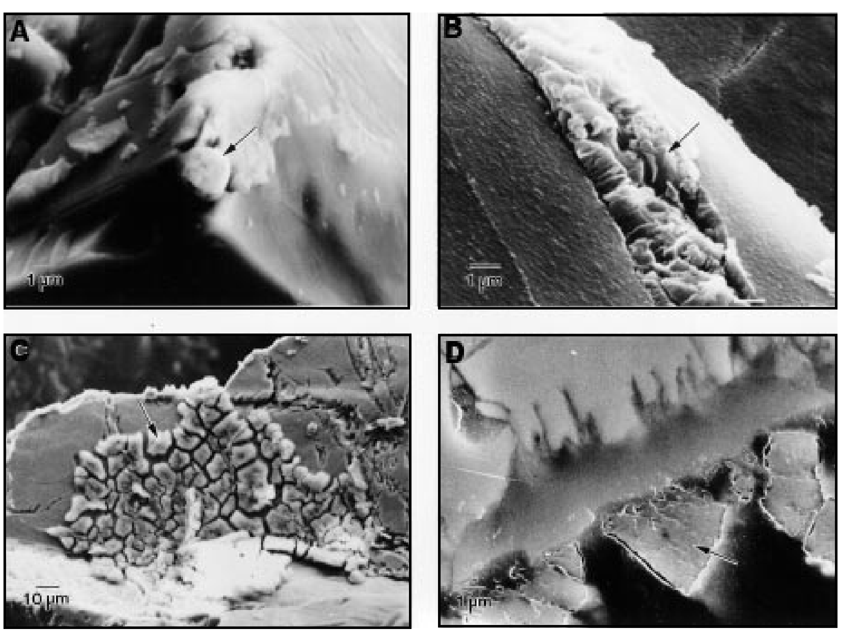
How much was there? Where is it now?

The morphology of Mars indicates that abundant liquid water existed in its early history. Where did this water come from and where did it go? If the water was degassed from the martian mantle, we would expect to find evidence of water in igneous martian minerals. If such igneous phases show little evidence for water, that might suggest water-rich materials came as a late-stage accretion to the martian surface. If the martian crust has acted through time as a significant sink for surface water, then we might expect to find abundant hydrated minerals formed by weathering processes at the martian surface. What do martian meteorites tell us about these questions?

Martian meteorites are known to contain martian water (Figure 3), some in igneous minerals (e.g., amphibole and mica) that crystallized from water-bearing magmas, and some in weathering products. However, water identified in igneous minerals appears to exist in relatively low abundance (~0.1-0.5%), and this implies their parent magmas were low in water. It is not apparent that such concentrations are sufficient to produce the amount of degassed water required to generate martian fluvial features. Further, an analysis of the deuterium/hydrogen (D/H) isotopic ratio of water in meteorite apatite and other minerals shows large fractionated values similar to atmospheric hydrogen (see next topic), suggesting that even the water in this igneous phase may have been derived from the martian surface.

Those weathering products in martian meteorites that contain water include silicate clays, hydoxides, and various salts, all clearly formed by interaction at low temperature of liquid martian water with igneous minerals that comprise the meteorites. Several martian meteorites contain traces of precipitated minerals such as Ca-carbonate and Ca-sulfate (Figure 3). The nakhlite meteorites contain the most diverse suite of hydrated phases, including carbonates, sulfates, and layer-structured silicate clays (iron-rich smectites), often in association with ferric iron oxides and hydroxides. These mineral assemblages, as well as oxygen isotopic analyses of water extracted from the nakhlites (Figure 4), suggest that the altering water was cool by geologic standards (<100°C), possibly cold (~0°C), and strongly oxidizing.

Unlike the younger martian meteorites, 4.5 billion years old ALH84001 contains abundant inclusions of distinctively layered sequences of Ca-Mg-Fe-carbonates (Figure 5). One interpretation is that they formed in a warmer, more reducing aqueous environment than the Nakhlites—perhaps hydrothermal. Another interpretation is that they formed ina cool reducing aqueous environment. Preliminary analyses indicate that the carbonates may have been depositied in ALH84001 as early as 3.6 billion years ago. Thus, martian meteorites suggest aqueous activity may have persisted throughout martian history. Because martian meteorites never spent substantial time at the very surface, more highly weathered surface materials are likely to contain greater mineral diversity and higher concentrations of water-bearing phases, which is consistent with Viking chemical analyses of martian soils.



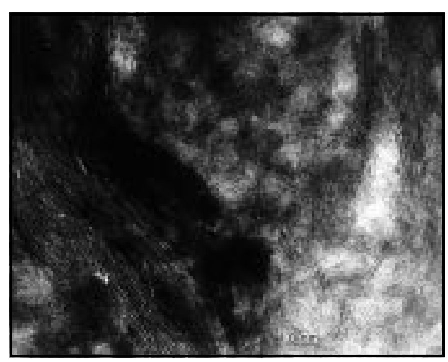


***Figure 3**. SEM images of hydrous minerals in Nakhla: A & B calcium carbonate, C magnesium sulfate, D calcium sulfate. TEM image of smectite clay and ferrihydrite in Lafayette.*

Figure 4. *(H. Karlsson, E. Gibson, JSC). This drop of water extracted from a martian meteorite has the unique stable isotope composition of martian crust.*

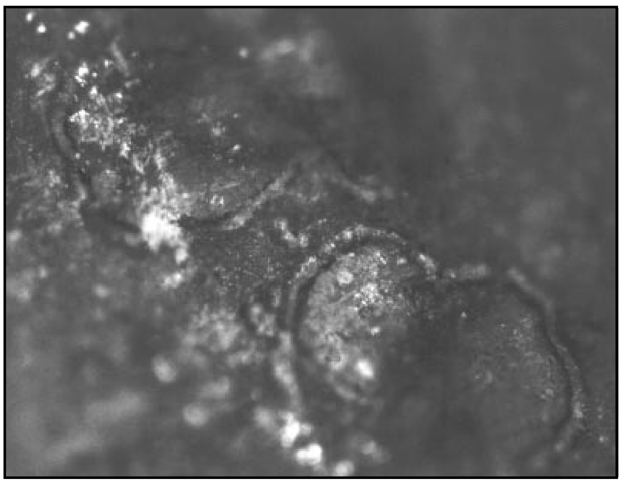


Figure 5. *(M. Grady, BMNH). Binocular view shows carbonate grains 100 microns across in ALH84001. Colored rings are due to variations in carbonate composition.*

Martian Atmosphere

What happened to the early martian atmosphere?

Just as the case for martian water (discussed earlier), other atmospheric species (e.g., carbon dioxide and Ar) were probably much more abundant early in martian history. What was the origin of these volatile elements (mantle degassing, late accretion of carbonaceous chondrites and comets?) and where have they gone? The isotopic compositions of several volatile elements measured in martian meteorites indicate that they have experienced mass fractionation, probably as a consequence of major atmospheric losses to space. What was the nature of these loss mechanisms (hydrodynamic escape, solar wind sputtering, solar UV ionization, giant impacts?) and when did they occur? Can the isotopic compositions of carbon and oxygen in martian surface materials define the nature of chemical and physical processes that have affected these elements over time?

Some elements in the martian atmosphere display large isotopic fractionations that suggest early loss of a major portion of the atmosphere (Figure 6). These data are: A D/H ratio (measured by earth-based spectra and in martian meteorite water) that is five times that of the Earth; a $^{15}N/^{14}N$ ratio that is 60% enriched over Earth's (measured by Viking and also found in martian meteorites); A $^{38}Ar/^{36}Ar$ ratio that is 30% enriched over Earth's, and a $^{136}Xe/^{130}Xe$ ratio that is 16-25% enriched over solar Xe and that found in carbonaceous meteorites (both Ar and Xe measurements are from shock-implanted gases in EETA79001). In contrast, Kr isotopes in EETA79001 closely resemble solar Kr, as do Xe isotopes in Chassigny. A minor component of N in EETA79001 and Zagami has a $^{15}N/^{14}N$ ratio similar to Earth's and quite different from Mars' atmospheric N. These findings indicate that at least two reservoirs of these gases exist on Mars, one a mass-fractionated atmospheric component and one likely an unfractionated mantle-derived component (Figure 6). How can such different reservoirs be used to define in detail the volatile evolution of Mars?

Isotopes of O and C in water and carbonates of martian meteorites show much less fractionation than expected due to atmospheric loss. This is probably because losses of these elements are buffered by condensed phases such as crustal water and carbonate. Even so, variations in $^{13}C/^{12}C$ among analyses are greater than one expects from equilibrium reactions. Has the martian $^{13}C/^{12}C$ changed with time, and if so can this be used to determine martian volatile evolution? Values of $^{18}O/^{16}O$ in ALH84001 carbonate are also about 1% enriched over oxygen in silicate, but $^{18}O/^{16}O$ in martian water is less enriched (Figure 7). Therefore, a potential exists for using these

Viking Lander 2 image. *Frost on martian surface.*

differences to deduce the temperatures and CO_2/H_2O ratios for equilibrium reactions involving these two species with silicates. Future analysis of returned martian surface materials containing a wider variety and abundance of C, O, and other volatile species (e.g., S, halogens) offers great potential for deciphering the long-term volatile evolution of Mars.

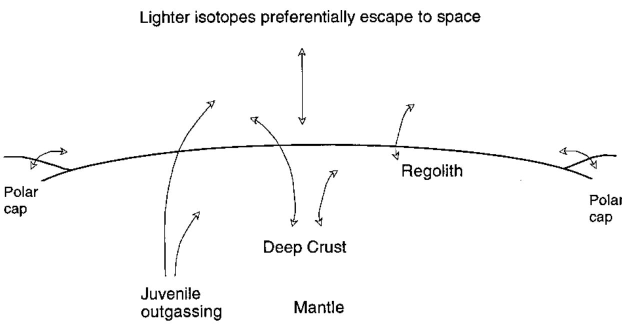


Figure 6. *Cartoon illustrating some processes through which isotopic fractionation of volatiles can occur.*

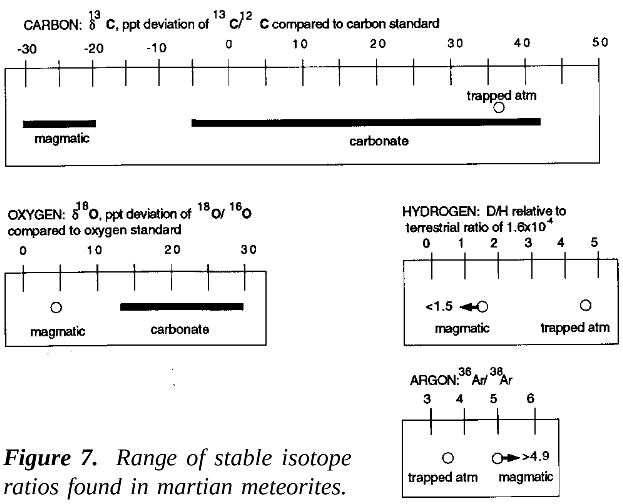


Figure 7. *Range of stable isotope ratios found in martian meteorites.*

Possible Life on Mars

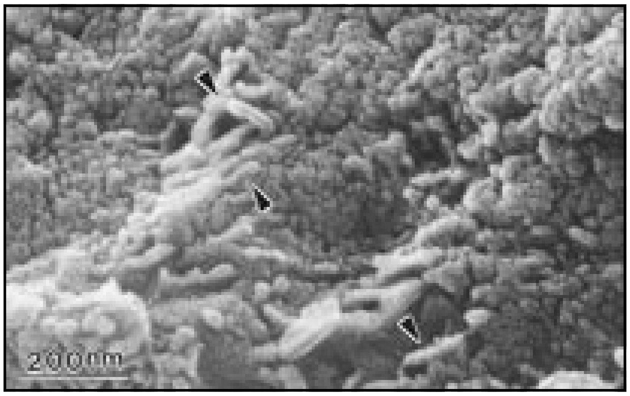
When and Where?

Since life requires liquid water, the history of water on Mars controls when and where life may have originated and flourished. The denser atmosphere early in Mars history contributed to a warmer, wetter environment. These are conditions more favorable for life. Traditional wisdom also directs the search for evidence of life to regions of water-lain sediments. Do the martian meteorites support these ideas? Can characteristics of possible martian life or habitat

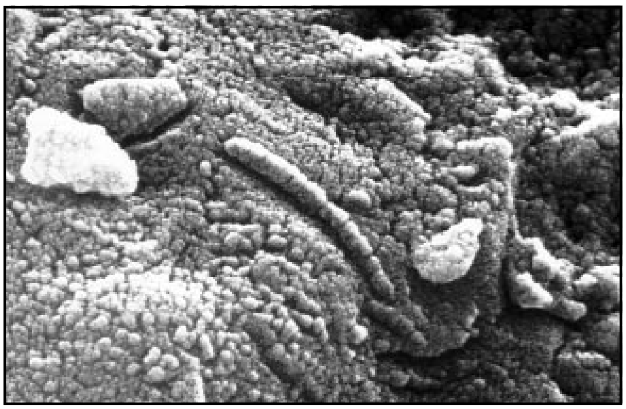
Whole rock, ALH84001. *The oldest martian meteorite.*

be inferred from meteorite evidence?

The recent findings of evidence for possible fossil life in the oldest martian meteorite ALH84001, the only martian meteorite dating back to this early period when conditions for life were more hospitable, do reinforce the idea of searching for life in Mars' ancient regions. Within the distinct, layered carbonates of ALH84001, lie four lines of evidence suggesting the possibility of life on early Mars. 1) Pancake-shaped features, up to 250 µm across with rims of layered Ca-Mg-Fe carbonates, are found along fractures and in pore spaces in the meteorite through which a fluid penetrated. They resemble some terrestrial bio-deposition features (Figure 5). 2) Martian-origin polycyclic aromatic hydrocarbons (PAHs), detected at very low levels by laser-excitation mass spectrometry, are associated with the fracture zones. The PAH compositions are few in number and relatively simple ring structures, consistent with remains of in-situ chemical decay biological cyclic compounds. 3) Very high resolution transmission electron microscopy (TEM) reveals the coexistence of tiny grains of magnetite and iron sulfides with a morphology and composition similar to grains deposited biogenically. A complex oxidation-reduction environment would be needed to account for this co-precipitation inorganically. 4) Finally, high resolution scanning electron microscopy has revealed within the carbonate fracture zones ovoid features, 20 to 100 nanometers across, that resemble nannobacteria recently detected on terrestrial rocks. Although individually these four lines of evidence have



Close view of central region of carbonate (away from rim areas) showing textured surface and nanometer ovoids and elongated forms (arrows). They resemble nanobacteria found in some terrestrial rocks.



This electron microscope image shows tubular structures of martian origin that may be fossils of organisms.

alternative, inorganic process interpretations, taken as a whole, biogenic activity is the simplest explanation to describe the observed features.

Indeed, if this evidence for fossil life is confirmed, it is an indication that hydrothermal environments in ancient igneous rocks are additional niches in which to search for martian life.

Sample Return

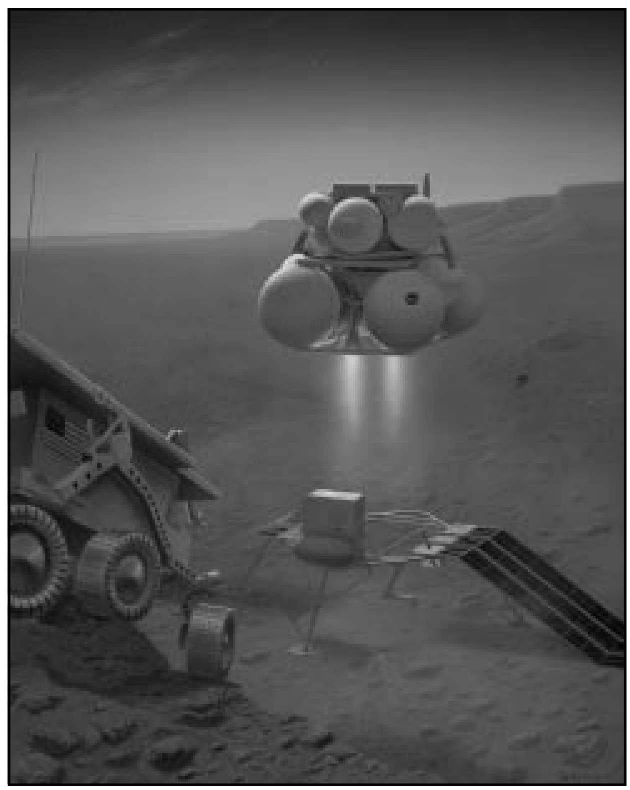
Why do we need a martian sample return?

Martian meteorites have provided a wealth of information about martian petrologic evolution, some clues to the nature of the martian hydrosphere and atmosphere and important clues in the search for life on Mars. There are, however some major limitations in using meteorites to model Mars' history.

Martian meteorites are from uncertain, random locations, not sites selected to answer major questions about Mars' history. Ideally we need samples from at least two known locations, one on old cratered highlands and one on young volcanic plains. Analyses of these samples on Earth would provide ground truth for remote sensing and calibrate the martian crater-age trend.

The second limitation is that martian meteorites are not representative of the martian surface. They are subsurface igneous rocks, not surface soils or sediments, and are thus not ideal as ground truth. They also represent extremes of ages of martian geologic provinces - ancient (4.5 Ga) highlands and very young (1.3 Ga or less) basalts and cumulates. We would like samples that are spread through martian history, especially samples bracketing the time of purported martian climate change. Soils and sediments, rather than igneous rocks, are needed to better understand martian weathering and atmospheric evolution and to search for prebiotic chemistry and possible fossil life.

To better understand Mars' geologic history we need returned samples from two or more carefully selected locations. Samples of soil and rocks



Martian sample return mission *(D. Kaplan, JSC). One scenario for a future martian sample return is the MISR (Mars In-situ Resources Sample Return) mission which cuts costs by relying on martian atmosphere to produce the oxygen for the return trip to Earth.*

returned by intelligent robotic rovers could significantly improve our knowledge of Mars. But to really solve the problem we may have to wait for humans to walk on mars and use our acute visual and mental systems to find the best samples.

Distant Shores. *After driving a short distance from their habitats, two astronauts stop to inspect a previously deployed robotic lander and its small rover that had been used to deliver a sample from this potential landing site to Earth.*

References

Review paper:

McSween H. Y., Jr. (1994) What we have learned about Mars from SNC meteorites. *Meteoritics* 29, 757-779.

Recent updates:

Gladman B. J., Burns J. A., Duncan M., Lee P., and Levison H. F. (1996) The exchange of impact ejecta between terrestrial planets. *Science* 271, 1387-1392.

Jakosky B. M. and Jones J. H. (planned publication early 1997) The history of martian volatiles. *Rev. Geophysics*.

McKay D. S., Gibson E. K., Jr., Thomas-Keprta K. L., Vali H., Romanek C. S., Clemett S. J., Chillier X. D. F., Maechling C. R., and Zare R. N. (1996) Search for past life on Mars: Possible relic biogenic activity in martian meteorite ALH84001. *Science* 273, 924-930.

Mittlefehldt D.W., (1994) ALH84001. a cumulate orthopyroxenite member of the martian meteorite group. *Meteoritics* 29, 214-221.

Romanek C. S., Grady M. M., Wright I. P., Mittlefehldt D. W., Socki R. A., Pillinger C. T. and Gibson E. K., Jr. (1994) Record of fluid-rock interactions on Mars from the meteorite ALH84001. *Nature* 372, 655-657.